

Mitigation options for carbon dioxide emissions from buildings

A global analysis

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Between 1971 and 1992, growth in carbon dioxide (CO₂) emissions from buildings varied widely by region, ranging from 0.9% per year in the industrialized countries to 0.7% per year in Eastern Europe and the former Soviet Union and 5.9% per year in developing countries. This paper outlines energy efficiency improvements for buildings and the overall technical potential to reduce CO₂ emissions by cutting growth in energy consumption in buildings. Three scenarios of future buildings CO₂ emissions in 2020 were developed. Under the business as usual scenario, buildings emissions increase 90% over 1990 levels. A scenario that involves adopting more efficient energy using practices and technologies is estimated to produce CO₂ emissions 50% above 1990 levels. A scenario with powerful incentives for energy efficiency could lead to CO₂ emissions 28% above 1990 levels. Much of the CO₂ growth is the result of population growth and growth in energy services, especially in developing countries. Policy instruments to reduce energy use and related CO₂ emissions include real increases in energy prices, aggressive use of energy efficiency policies, major programs to transfer knowledge, technology, and tools for transforming markets to the developing world and continued efforts to pursue research and development in technologies and practices to increase energy efficiency in buildings. Copyright © Elsevier Science Ltd.

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Carbon dioxide (CO₂) emissions result from the production, distribution, and use of fossil fuels and electricity to provide such end use ‘services’ as cooking, space heating and cooling, lighting, refrigeration and freezing, and water heating in buildings. A wide variety of fuels is used to provide energy for the buildings sector. Coal, oil and natural gas are all used for heating as well as for the production of electricity. Electricity, in turn, is used to provide power for lighting, heating, cooling and appliances. When combusted, all of these fuels emit carbon to the atmosphere. Currently, energy-related CO₂ emissions account for 74% of all anthropogenic CO₂ emissions (IPCC, 1992). In 1992 104 exajoules (EJ)¹ of energy were used in this sector, resulting in the release of over 1600 Mt carbon (C).

Recent studies for the World Energy Council and the United Nations Division for Sustainable Development show

that approximately 33% of global primary energy is consumed by residential and commercial buildings and that demand for energy in this sector could be greater than any other sector in 2020 (WEC, 1995; Worrell *et al.*, 1996). These studies grouped countries of the world into three regions: industrialized countries (also referred to as Organization for Economic Cooperation and Development, or OECD, countries); Eastern Europe and the former Soviet Union (EE/FSU); and developing countries² to assess regional historical building energy demand and to develop scenarios of building energy demand for the year 2020. Conversion of these energy values to CO₂ emissions indicates that in 1992 industrialized countries produced about

¹ 1 EJ = 23.833 Mtoe = 1/1.054 quadrillion Btu.

² We recognize that these divisions hide significant regional differences, especially in the category of developing countries. Future work will further disaggregate these three regions, more closely grouping countries in terms of level of economic development.

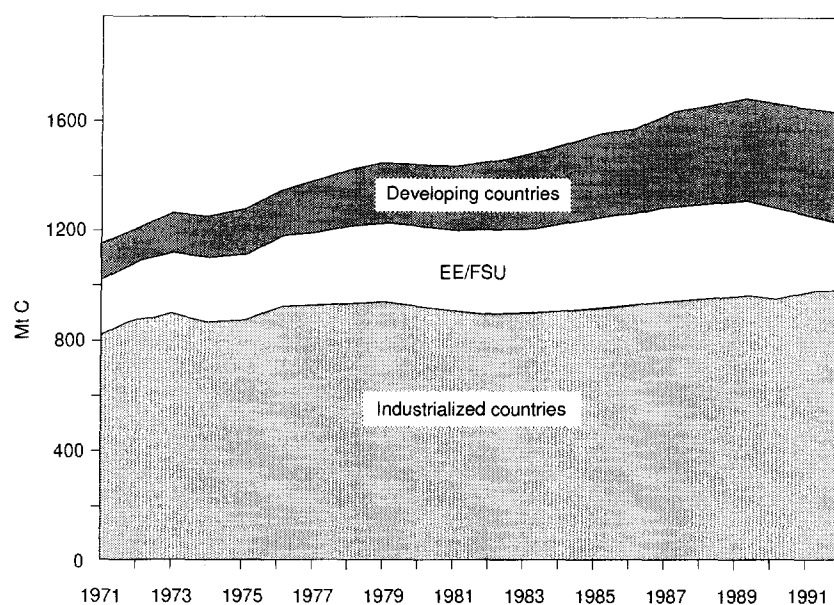


Figure 1 World CO₂ emissions from buildings by region, 1971–92

Source: WEC (1995); Wiel *et al* (1996).

Table 1 World CO₂ emissions from buildings

Region	CO ₂ emissions (Mt C)					Average annual growth rate (%)			
	1971	1980	1988	1990	1992	1971–1988	1971–1990	1971–1992	1988–1992
Industrialized countries	812	916	955	950	975	1.0	0.8	0.9	0.5
EE/FSU	208	306	358	334	243	3.2	2.5	0.7	–9.2
Developing countries	124	223	355	380	413	6.4	6.1	5.9	3.9
World	1144	1445	1668	1664	1632	2.2	2.0	1.7	–0.5

Source: WEC (1995); Wiel *et al* (1996).

60% of CO₂ emissions as a result of energy use in buildings, developing countries produced about 25%, and the EE/FSU produced about 15% (Levine *et al*, 1996; Wiel *et al*, 1996).³

The most significant factors affecting growth in energy use and subsequent CO₂ emissions are demographics (population growth and urbanization), demand for energy using services, energy intensities of the technologies used to provide those services, and the carbon intensity of fuels used directly in buildings or to produce electricity. This paper presents historic trends in global buildings CO₂ emissions,

the potentials for reducing buildings CO₂ emissions through reductions in buildings energy use, and three scenarios of buildings CO₂ emissions in 2020.

Historic trends in building sector CO₂ emissions

Figure 1 shows CO₂ emissions from the buildings sector for industrialized countries, the EE/FSU and developing countries between 1971 and 1992. During this time, global CO₂ emissions caused by energy consumption in buildings grew at an annual average rate of 1.7%. This growth, however, varied widely by region: 0.9% per year in the industrialized countries, 0.7% per year in the EE/FSU, and 5.9% per year in the developing countries (see Table 1). Emissions in the EE/FSU grew at an average rate of 3.2% per year between 1971 and 1988, but declined at an average of 9.2% per year between 1988 and 1992 due to the significant decrease in energy consumption that followed the economic collapse in that region.

In 1992 about 1600 Mt C were emitted as a result of energy use in buildings worldwide. While CO₂ emissions from the industrialized countries and the EE/FSU were

³The data do not include emissions of CO₂ from biomass fuels. Although their use in the residential sector of many developing countries is considerable, past and current consumption levels are very uncertain. Further, it is difficult to determine what fraction of biofuels consumption represents net emissions. Hall (1991) derived national estimates of biomass consumption for nearly all developing countries; the total for 1988 for all sectors amounts to 36 EJ, not far below the 47 EJ of commercial energy consumption. (Buildings account for an estimated 80–90% of the total biomass use.) The range of uncertainty around this estimate is difficult to assess, since the information base from which national estimates of biofuels use are made is weak. We note that if we did include the effects of fuel switching from biomass in the analysis, it would cause CO₂ emissions to increase even further than predicted under a base case.

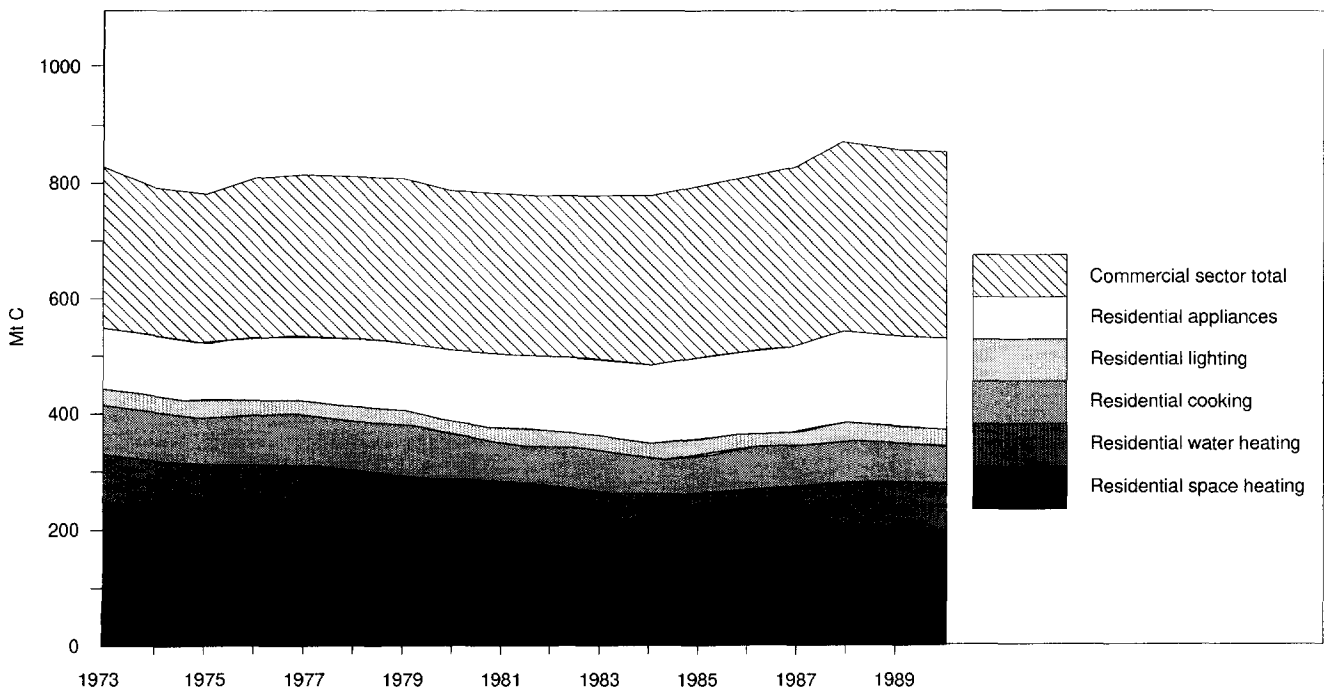


Figure 2 CO₂ emissions from residential and commercial energy consumption in the USA, Japan, former West Germany, France, UK, Italy, Sweden, Norway and Denmark

Source: Scheinbaum and Schipper (1993); Cooper (1993).

about 20% higher in 1992 than 1971 levels, emissions from the developing countries were over 200% higher because of population growth and increase in per capita levels of energy services. We estimate that the residential and commercial sectors accounted for 19 and 10%, respectively, of global CO₂ emissions from fossil fuels in 1990 (Levine *et al*, 1996).

Industrialized countries

CO₂ emissions In 1992 energy use in buildings in industrialized countries was responsible for 975 Mt C. Figure 2 shows that residential buildings account for two-thirds of total CO₂ emissions from buildings in nine industrialized countries. 1990 emissions from energy use in residential buildings in these countries were slightly lower than levels in the early 1970s. Emissions from commercial buildings rose 15% during the period. This increase reflects both the growth in floor space and the increased share of energy service demands met by electricity. Figure 2 also shows emissions for residential energy disaggregated by end use (Scheinbaum and Schipper, 1993; Cooper, 1993). Space heating and appliances dominate, accounting for 38 and 30% of residential CO₂ emissions, respectively.

Energy consumption Residential building energy use in industrialized countries grew 1.4% per year between 1971 and 1992. The number of households grew 1.5% per year faster than population during this time (Schipper and Mey-

ers, 1992), leading to increased demand for energy for various residential services, particularly for space heating, central air conditioning, water heating and energy intensive appliances (refrigerators, color televisions and clothes washers). For example, in the UK the fraction of residences with central space heating grew from 43% in 1974 to around 65% in 1983 (Ketoff *et al*, 1987). In 1970 only one-third of new single family homes in the USA had central air conditioning; by 1990 this number had climbed to over three-fourths (US Congress, OTA, 1992a).

At the same time, there has been a significant reduction in the energy required to deliver various services, particularly in technologies such as space-heating furnaces, refrigerators, and lighting systems. New refrigerators in the USA, for example, use about 40% of the energy of new refrigerators sold in the early 1970s (US Congress, OTA, 1992a). Since 1973, space heating intensity (useful energy per m² of floor area) has declined in seven OECD countries. Also, the following declines were experienced in appliance stock average unit energy consumption values between 1972 and 1992: refrigerators – 17% (USA); clothes dryers – 13% (USA) to 26% (former West Germany); dishwashers – 46% (USA) to 63% (former West Germany); clothes washers – 6% (USA) to 49% (former West Germany) (Schipper *et al*, 1996).

Growth in energy use in commercial buildings in industrialized countries averaged 2.6% per year between 1971 and 1992, nearly twice the rate of residential buildings. This growth in energy use in commercial buildings was in

large part caused by increases in electric heating, computers, and other office equipment as well as growth in commercial floor space (Schipper and Meyers, 1992). The USA has the largest amount of commercial floor space per capita, but growth is highest in countries such as Japan (4.1% per year), Finland (4.1% per year) and Norway (3.6% per year). The average growth in floor space for a sample of ten OECD countries was 2.3% per year from 1970 to 1990 (Sezgen and Schipper, 1995).

Some of the increase in commercial buildings energy demand has been counteracted by improved insulation and more efficient lighting and other equipment. Newer commercial buildings are designed more appropriately for their climate, are better insulated, and have more efficient space-conditioning equipment and lighting. Older buildings are becoming more efficient as improved technologies are incorporated in the course of normal building renovation. A recent survey of US buildings found that some energy efficiency measures had been installed in 95% of US commercial floor space (EIA, 1994).

Developing countries

CO₂ emissions Carbon emissions from energy use in buildings in developing countries were about 400 Mt C in 1992. However, emissions grew at a rapid 5.9% per year on average between 1971 and 1992. The residential sector is estimated to account for 70% of total buildings CO₂ emissions in developing countries (Sathaye and Ketoff, 1991).

Energy consumption Rapid economic growth and population increases in developing countries are bringing large increases in energy consumption in all sectors as countries expand their basic infrastructures. From 1971 to 1992 purchased energy consumption for commercial and residential buildings in developing countries grew 6.7% per year and 5.7% per year, respectively, slightly more than twice the world average.

Residential buildings in developing countries account for 75% of buildings energy consumption, and the share would be even higher if (non-commercial) biomass energy were included. As developing country economies mature, increasing urbanization and substitution away from traditional fuels to commercial fuels will also increase purchased energy demand in residential buildings.

Because of the strong correlation between income level and ownership of appliances, demand for energy services such as refrigeration, television and space conditioning will increase as economies expand. Saturation levels of various residential appliances for selected developing countries are shown in Table 2, indicating that a large potential exists for much increased market penetration in many countries. Air conditioners and refrigerators account for a significant portion of residential electricity use by appliances. Rapid increases in appliance ownership in developing countries are likely in the coming years; such growth will lead to large increases in residential electricity demand (Levine *et al*, 1996; US Congress, OTA, 1992b). The energy intensity of appliances used in developing coun-

Table 2 Comparison of saturation levels for residential appliances in selected developing countries (%)^a

Country	Refrigerator	Color television	Air conditioner	Clothes washer
Brazil ^b	66	35 ^c	4	22
China ^d	19	30	1	34
India	14–40 ^e	17–38 ^e	0–2 ^e	8 ^f
Mexico ^g	58	55 ^h	6	42
Thailand ⁱ	63	117	18	22

^aFor comparison, refrigerator saturation levels in nine industrialized countries in 1988 were between 106% and 117% (indicating more than one refrigerator per household) and clothes washer saturation levels were between 73% and 99% (Schipper and Meyers, 1992); ^bMeyers *et al* (1990); ^cJannuzzi and Schipper (1991); ^dSinton (1995) (based on 1993 data); ^eTyler *et al* (1994) (based on three cities surveyed); ^fSathaye and Tyler (1991); ^gMasera *et al* (1993); ^hFriedmann (1995); ⁱThailand Load Forecast Subcommittee (1993).

tries, when normalized for size and features, is often higher than that of similar appliances used in industrialized countries, implying a significant potential for future savings. Studies in China, Egypt, India, Indonesia and Mexico have found that the appliances produced locally were significantly less efficient than world standards (Dutt, 1993; Levine *et al*, 1991; Liu, 1993).

Currently, demand for energy using services in commercial buildings varies considerably. In India lighting is estimated to account for 50% of total electricity followed by space conditioning and refrigeration (40%). In Mexico, the share of lighting can be even higher, while in Thailand space conditioning accounts for 40 to 60% of total building energy demand (Busch, 1995; de Buen, 1995). In most developing countries, the growth in energy use in commercial buildings – expected to continue near the recent level of about 5% per year – is driven by substantial growth in illuminated and air-conditioned commercial floor space.

Eastern Europe and the former Soviet Union

CO₂ emissions In 1992 about 240 Mt C were emitted from buildings in the EE/FSU. Average annual growth in emissions was 3.2% between 1971 and 1988. After reaching a peak of 360 Mt C in 1988, emissions declined on average 9.2% per year through 1992.

Energy consumption Between 1971 and 1988, residential energy use increased at a rate of 3.9% per year and energy use in commercial buildings increased at 6.6% per year in the EE/FSU, resulting in a 4.7% annual increase in energy used in all buildings over this period. Much of the EE/FSU building stock has inefficient space conditioning systems and energy using equipment, as well as poorly insulated building envelopes, and therefore requires more energy to provide the same level of energy services as a similar building in industrialized countries. For example, buildings in the FSU require 50% more energy to heat a square meter of floor space (after correcting for weather) than buildings in the USA (Cooper and Schipper, 1992). Building energy use has been affected by the economic restructuring in the region since the late 1980s, leading to an average annual de-

cline in buildings energy use of 3.8% between 1988 and 1992. This decline is expected to be temporary, however, as growth in the number of new buildings and the energy services within those buildings is anticipated for both the residential and commercial buildings sectors.

In the residential sector, the largest end uses are space heating, water heating, and cooking. The majority of the population in the EE/FSU lives in multi-family housing. The number of residents per household is declining, leading to an increase in per capita floor space and per capita energy use. For example, the number of residents per unit in Poland dropped from 3.65 to 3.46 between 1978 and 1988. In the Czech Republic residents per unit dropped from 2.92 to 2.76 between 1980 and 1991 (Meyers *et al*, 1995). This has led to a modest increase in per capita living area thereby driving up the demand for particular end uses such as space heating. Residential living area per capita in the FSU increased 2.3% annually between 1972 and 1987 from 11 m² per capita to 15.5 m² per capita (Cooper and Schipper, 1992). Residential floor space per capita, estimated to be 16 to 17 m² per person in Poland and the Czech Republic, has also increased at similar rates (Meyers *et al*, 1995). Per capita floor space is still significantly less than levels in Europe (25 to 33 m² per person), Scandinavia (34 to 45 m² per person), or the USA (61 m² per person), suggesting that large future increases in floor space and related buildings energy use could take place as the economic growth continues (Meyers *et al*, 1995; Schipper and Meyers, 1992; US Congress, OTA, 1993).

Primary energy use in the FSU commercial buildings sector grew at a rate of 3.4% per year between 1970 and 1988, from 2.1 EJ to 3.9 EJ (Cooper and Schipper, 1992). In Poland, primary energy use for this sector grew from 0.3 EJ in 1970 to a peak of 0.7 EJ in 1987, at an average growth rate of 5% annually. Consumption dropped by over 9% per year after that, to 0.4 EJ in 1992. In general, the commercial sector in the EE/FSU is poorly lit, has little electrical office equipment, and has equipment that is less efficient than in industrialized country commercial buildings (Meyers *et al*, 1994a, 1994b; Schipper and Martinot, 1993). Commercial sector floor space in the FSU grew from less than 3.0 m² per capita in 1970 to about 5.5 m² per capita in 1987, a growth of 1.2% per year (Schipper and Martinot, 1993; Schipper and Meyers, 1992). Like the residential sector, the per capita floor space is much lower than the typical 10 to 16 m² in Western Europe and 25 m² in the USA (Schipper and Martinot, 1993), suggesting that a large potential exists for growth in commercial sector energy demand. Per capita energy use in the commercial sector in Poland has already begun to rebound and strong growth in the private retail sector driving an expansion of the commercial building stock is expected (Meyers *et al*, 1994a).

Potential for reducing CO₂ emissions through increased energy efficiency of buildings

There are several categories of energy efficiency improvement potentials. The theoretical potential of energy effi-

Table 3 Technical potential for energy efficiency improvement in residential and commercial buildings^a

Sector	Potential (%)	Country/region
Residential	48 ^b	USA
	27–46 ^c	USA
	29 ^c	USA
	36 ^d	USA
	60 ^e	France, Germany, Italy, the Netherlands, UK
	42–76 ^d	The Netherlands
Commercial	31 ^h	Brazil
	23–49 ^c	USA
	55 ^e	USA
	65 ^f	France, Germany, Italy, the Netherlands, UK
	41–74 ^g	The Netherlands
	60 ⁱ	Slovak Republic
Residential and commercial	38 ^h	Brazil
	45 ^c	USA
	43 ^j	Sweden

^aFrozen efficiency assumes that equipment and buildings are not retrofitted during the analysis period and remain at the same efficiency level until the end of the analysis period or until they are retired. It excludes those efficiency changes that would occur through market forces during the period. In many cases, about half of the energy savings in the technical potential curves might be achieved through market forces over a twenty-year time period. This convention is followed in order to more easily make comparisons between different studies; ^bKoomey *et al* (1991). Technical potential for electricity relative to frozen efficiency; ^cFaruqui *et al* (1990). Technical potential for electricity in the year 2000; ^dEIA (1990); Technical potential for total energy use in the year 2010; ^eRosenfeld *et al* (1993). Technical potential for electricity in 1989 relative to frozen efficiency; ^fKrause *et al* (1995). Technical potential for the year 2020; ^gde Beer *et al* (1994). Technical potential for total energy use in the year 2000 and 2015 respectively relative to frozen efficiency; ^hGeller (1991). Technical potential for electricity in the year 2010; ⁱKaan *et al* (1995). Technical potential for fuels (heating) in the near term; ^jBodlund *et al* (1989). Technical potential for electricity relative to frozen efficiency.

ciency improvement for a certain process is determined by thermodynamic laws. The technical potential is defined as the achievable savings resulting from the most effective combination of the efficiency improvement options available in the period under investigation. Applying economic constraints, we can also identify an economic potential for energy efficiency improvement, which is defined as the potential savings that can be achieved at a net positive economic effect ie the benefits of the measure are greater than the costs over the lifetime of the measure. The market potential is defined as the potential savings that can be expected to be realized in practice, and is determined by investment decision criteria applied by investors under prevailing market conditions.

Technical potentials for energy efficiency improvements in buildings

Table 3 presents an overview of the results of selected studies for the technical potential of energy efficiency improvement in residential and commercial buildings. Potential savings range from 23 to 76% depending upon the sector, the country or region, and other assumptions. Economic and market potentials, which only include those technologies and practices that are cost-effective and are selected by

consumers in the marketplace, are lower. One study of electricity efficiency in residential buildings estimates that 45% of the technical potential during the period 1990 to 2010 is likely achievable in the market (Brown, 1994).

A study of CO₂ reduction potentials in residential buildings in Japan found that with strong efforts to implement cost-effective energy efficiency measures, CO₂ emissions are projected to increase 7% to 23% above 1990 levels in 2010 compared to the expected increase of 50% above 1990 levels without energy efficiency improvements. Adoption of energy efficiency measures over the long term (2020 and beyond), allowing for more building and equipment stock turnover, is estimated to maintain CO₂ emissions from energy use in residential buildings at 1990 levels in Japan. For commercial buildings, it is estimated that CO₂ emissions in 2010 can be reduced from the expected 25% increase above 1990 levels to about 12% above these levels primarily through improvements in space conditioning and lighting. Over the long term, it is estimated that CO₂ emissions from energy use in commercial buildings can be held to about 70% of 1990 levels (Japanese Environment Agency, 1992; Tsuchiya, 1990).

In India savings of 40 Mt C, or 35% of 1987–88 emissions, are estimated to be possible in the residential sector through implementation of various energy efficiency measures, such as replacement of kerosene lamps by fluorescent lamps. In 2010 this 35% savings translates to about 120 Mt C due to the projected rapid increase in both population and per capita demand for energy services (Govinda Rao *et al*, 1991; Levine *et al*, 1996).

Energy efficient technologies

For residential and commercial buildings, efficiency improvements can be made in building envelopes, space conditioning, water heating, refrigeration, clothes washers and dryers, cooking equipment, lighting, motors and through the application of building energy management systems. The technologies to achieve these efficiency gains apply to all modern buildings, whether in the industrialized countries, the EE/FSU, or the developing world. Table 4 describes some of the energy efficiency improvements that can be made in buildings worldwide. Below we briefly review the potential for energy savings in buildings envelope, heating and cooling equipment, lighting, motors, cooking and office equipment. We also discuss building energy management systems and building commissioning, operation, and management.

Building envelopes Energy use can be reduced with building designs that include proper orientation, adequate insulation levels, proper sealing, overhangs, and high quality windows. Improvements in the thermal characteristics of windows and increases in wall and ceiling insulation in residential buildings in China can reduce energy use by 40% relative to mid-1980s practice while allowing for a considerable increase in indoor temperatures (Huang, 1990). A West German study that evaluated homes of different vintage in five building types found that investments saving

40% of baseline heating energy would be cost-effective (Ebel, 1990). In the USA a government study estimated that energy savings of 30 to 35% could be attained over the 1990–2010 period through retrofits in dwellings built before 1975 (EIA, 1990). Adoption of Swedish building practices, which rely heavily on assembly from factory built components, in the rest of Western Europe and North America would bring a reduction of at least 25% in the space heating requirements of new dwellings relative to those built in the late 1980s (Schipper and Meyers, 1992).

Heating and cooling equipment Use of condensing technology or high efficiency heat pumps can reduce energy use for heating. Technical efficiency improvements for district heating systems include better insulation of pipes that carry heat to and among buildings and improvement of the operation and control of heating systems. Technologies to increase air conditioner efficiency include better thermal insulation, larger and/or improved heat exchangers, higher evaporator coil temperatures, advanced refrigerants, more efficient motors, dual-speed or variable-speed compressors and more sophisticated electronic sensors and controls (Morgan, 1992; Geller, 1995). For commercial buildings, large air conditioning systems using rotary or centrifugal compressors are typically more efficient than systems based on reciprocal compressors or smaller air conditioning units. Efficiency improvements generally come from improving the efficiency of the chiller, routing and designing ducts to minimize losses, switching to a system using a heat pump, improved controls, improved maintenance, and reducing demand (US Congress, OTA, 1992a). For US residential electricity heating and cooling measures, one estimate found a technical savings potential of 12% of total frozen efficiency space conditioning energy use in 2010 (Koomey *et al*, 1991).

Lighting Lighting accounts for a significant portion (approximately 10 to 20%) of electricity use in all countries. In most developing countries, lighting is the most important electric end use. About 35% of the world's population does not have electricity and instead relies on kerosene lamps (Efforset and Farcot, 1994). Replacing such lamps with 16 watt compact fluorescent lamps (CFLs) will increase light output 22-fold, while reducing the fuel use rate by a factor of 8, even including electricity generation losses (van der Plas, 1988). In households and commercial establishments that have electricity, use of CFLs instead of incandescent lamps (along with other technical improvements) can significantly reduce electricity demand. Studies of cost-effective energy savings for lighting in commercial buildings in different countries have produced a range of savings estimates: 35% for the USA (Atkinson *et al*, 1992); between 36 and 86% for five countries in Western Europe (Nilsson and Aronsson, 1993); 70% in Thailand (Busch *et al*, 1993); 22% in Brazil (Jannuzzi *et al*, 1991); and 35% in India (Nadel *et al*, 1991).

Table 4 Summary of energy efficiency improvements for various buildings sector end use services

Service	Technology/practice	Energy-efficiency improvements
Building envelope	Windows	Use double glazed windows at a minimum. Low-e coatings reduce heat losses by about one-third; double pane window with gas filled spaces and two suspended reflective films inside reduces heat losses by 75%; use of thermal breaks to limit conduction losses through the frame
Space conditioning	Insulation	Adequately insulate ceilings and walls
	Ducts	Reduce or eliminate leaks
	Furnaces	Condensing furnaces are 90% to 97% efficient (compared to US minimum efficiency standard of 78% for new gas fired warm air furnaces)
	Heat pumps	Electric air source heat pumps are about twice as efficient as electric resistance heaters. Ground source heat pumps are even more efficient
	District heating	Increase insulation of pipes, repair inoperative radiator valves, install thermostats and individuals meters; improve operation and control of heating systems
Water heating	Water heaters	Air conditioners
		Use better internal insulation, larger heat exchanges, higher evaporator temperatures, dual speed or variable speed compressor motors to reduce on-off cycling, more efficient rotors and compressors, advanced refrigerants, and more sophisticated electronic sensors and controls
Refrigeration	Refrigerators	Increase insulation of water heaters; use electronic ignition for gas water heaters and higher efficiency gas burners. Use air source, exhaust air and ground source heat pump water heaters
Clothes washing/drying	Clothes washers	Use of advanced compressors, evacuated panel insulation, and other features lead to refrigerators that consume half as much electricity per volume as those that meet the US 1993 appliance standards
Cooking	Clothes dryers	Change from vertical axis to horizontal axis technology, reducing energy use by about two-thirds. Increasing spin speed during the spin-dry cycle of a clothes washer can reduce drying energy use by 30% to 50%
	Biomass stoves	Use heat pump dryers, leading to savings of 70% over conventional dryers
Lighting	Compact fluorescent lamps	Improved biomass stoves can reduce the fuel used for cooking a standard meal by 30% to 40%. An additional 50% fuel savings results from switching to kerosene stoves. Solar ovens can also replace biomass stoves
	Fixtures	Replace incandescent lamps with CFLs which require 75% less electricity
	Ballasts	Use specular reflective surfaces inside a fluorescent lamp fixture, increasing light emitted and allowing for removal of lamps (declamping)
Motor power	Lighting control systems	Electromagnetic ballasts reduce ballasts losses to about 10% (versus 20% of magnetic ballasts). Solid state electronic ballasts increase the efficiency of the ballast/lamp system by approximately 20% to 25%
		Savings of 10% to 15% with photocell controls, 15% to 30% with occupancy sensors, and up to 50% in perimeter zones with daylighting dimming systems. Also use multi-level switches, timers and task lighting
		Savings of 15% to 40% over a standard motor depending on application
Energy management	Variable speed drives	Savings of 2% to 15% over a standard motor depending on the motor size
	Energy efficient motors	Optimal sizing of motors, pumps, fans, compressors and cables can reduce losses. A good maintenance program can reduce motor electricity by up to 10% to 15%
Building performance assurance	Specifying and maintenance	Systems range from point of use timers to complex microprocessor based systems that minimize unnecessary equipment operation and provide other functions such as economizer cycling or varying supply of air or water temperatures and limiting peak electric loads by selectively switching off or cycling loads
	Building energy management systems	Recent building performance case studies suggests that typical savings of about 15%, and as much as 40% of annual energy use can be gained by compiling, analyzing, and acting upon energy end use data

Source: Claridge *et al* (1994); Levine *et al* (1996); Levine *et al* (1995).

Motors Motors are the largest end user of electricity in most countries. Motor electricity use can be reduced through use of energy efficient motors, variable-speed drives, and other controls as well as through improvements in power quality, specifying and maintenance practices, and drivetrain components. A high efficiency motor reduces energy use by 2% to 15%, depending on the motor size. Energy savings of 15% to 40% are possible using variable speed drives (Nadel *et al*, 1991).

Cooking Cooking is the largest home energy use in most developing countries, but a relatively minor end use in the industrialized countries and the EE/FSU. In the industrialized countries, there is relatively limited potential (10% to

20%) to improve the energy efficiency of primary cooking devices. In developing countries, use of improved wood-burning stoves can reduce the fuel used for cooking a standard meal by 30% to 40% (Leach and Gowen, 1987; Levine *et al*, 1996). Switching to a kerosene stove results in an additional 50% fuel savings (Dutt and Ravindranath, 1993).

Office equipment Office equipment is one of the fastest growing energy end uses in commercial buildings. It is estimated that energy saving power management hardware and software for personal computers, monitors, printer, copiers and fax machines can save 22% of projected US commercial sector electricity use by these products in 2010. Use of advanced technologies such as LCD screens and CMOS

Table 5 Estimated CO₂ emissions from buildings for three scenarios for the year 2020 (in Mt C)

Region	Emissions 1990	Business as usual		State of the art Emissions 2020	Growth (% pa)	Ecologically driven/ advanced technology	
		Emissions 2020	Growth (% pa)			Emissions 2020	Growth (% pa)
Industrialized countries	950	1207	0.8	1131	0.6	1016	0.2
EE/FSU	334	970	3.6	721	2.6	541	1.6
Developing countries	380	994	3.3	646	1.8	567	1.3
World	1664	3171	2.2	2498	1.4	2123	0.8

(complementary metal oxide semiconductor) chips coupled with the use of less energy intensive printers can lead to savings of almost 60% (Kooimey *et al*, 1995).

Building energy management systems Building energy management and control systems regulate the operation of heating, ventilation, air conditioning, and lighting in buildings. It is estimated that computerized energy management equipment typically provides 10 to 20% energy savings (Geller and Miller, 1988). A study in Texas identified potential annual energy savings of 23% of total building energy costs in 35 commercial buildings and 104 schools (Liu *et al*, 1994).

Building commissioning, operation and maintenance A major problem in all commercial buildings – even those that are designed and built to be energy efficient – is that they rarely perform as intended. There is a need to test buildings before or during early occupancy to verify that the design and equipment are performing correctly ('commissioning'). Periodic monitoring and maintenance to assure continued correct performance is required during the lifetime of the building. Period monitoring can save between 15 and 30% of annual energy use (Claridge *et al*, 1994).

Reducing urban heat islands Urbanization of the natural landscape, where vegetation is removed and roads and buildings (often made of dark-colored materials) are constructed, leads to a temperature difference between urban and rural areas and increases demand for cooling energy. A recent study estimates that carbon emissions in the USA in 2015 could be reduced by 27 Mt C through a nationwide program of planting urban shade trees and lightening surfaces. Similar programs in the industrialized countries of the world could approximately double these savings to 50 Mt C by 2015 or 2020 (Levine *et al*, 1996).

Scenarios of global buildings CO₂ emissions

Three scenarios for buildings carbon dioxide emissions during the period 1990–2020 were developed (see Table 5) based on previously developed energy use scenarios (WEC, 1995). In this conversion it is assumed that non-industrialized regions will switch to a less carbon-intensive fuel mix for electricity generation, but that the share of electricity and gas in building energy use will increase. Baseline emissions for 1990 are based on Marland *et al* (1994) and WEC (1995). Energy to carbon conversion is

based on UNEP *et al* (1995). The scenario assumes no net imports of electricity across regional boundaries. Emissions for 2020 are based on IEA (1995) and WEC (1995).

The quality of historical data on energy use and its determinants varies widely. There are considerable data on historical energy use by end use, as well as saturation and energy efficiency of appliances, HVAC equipment etc for residential and commercial buildings in OECD countries from 1972 to the present. These data are poorly known for most developing countries, with the exception of China where data on energy demand (excluding biomass) in buildings is known relatively well from 1980 to the present, and useful information energy use by end use and equipment saturation in residential buildings since 1980 is also available. There are considerable data on energy use in buildings in Eastern Europe and the USSR prior to 1988, although also with some major uncertainties. Since 1988, data on Eastern Europe and the former Soviet Union are poor. The most glaring deficiency in data for all regions concerns characteristics of existing and new buildings and the area of annual new construction. For non-OECD countries, data on saturation, usage, and efficiency of energy using equipment are poor. With some exceptions (in portions of some OECD countries) data on performance of actual buildings and equipment – as occupied and used – are limited.

In addition to data limitations, the scenarios have some methodological limitations. We did not build a stock turnover model to estimate future energy use in the scenarios, although we checked the results to assure that they were consistent with historical turnover. It was difficult to indicate precisely the assumptions regarding market penetration of energy efficient equipment and practices in the three scenarios, in large measure because of the lack of information on the efficiency, performance, and usage of existing and new buildings and equipment in large portions of the world.

In spite of these limitations, we believe the three scenarios described below represent well the range of likely energy demand in an economic future in which much of the developing world continues to have growing economies, Eastern Europe and later the former Soviet Union economies recover and rebuild to more closely resemble those of the OECD and OECD countries have slow, relatively steady economic growth. The three scenarios are distinguished primarily in the degree to which policies are put in place that promote the development and commercial acceptance of technologies and practices to use energy more efficiently in buildings. The refinement of these scenarios,

as well as full documentation of assumptions and data, is underway, with results expected in fall 1997 (Levine, 1996). Additional information on the existing scenarios can be found in WEC (1995).

For industrialized countries, the business as usual scenario assumes continued trends in energy efficiency improvement leading to CO₂ emissions growth rates of 0.8% per year, comparable to those seen between 1971 and 1990. Much higher growth in emissions is expected in the EE/FSU and in developing countries, mostly due to the great increase in demand for energy services in both of these regions. In the EE/FSU, energy efficiency improvements are assumed to increase somewhat faster than historical rates, leading to growth in CO₂ emissions of 3.6% per year, slightly higher than that experienced between 1971 and 1988. Growth in CO₂ emissions is assumed to be 3.3% per year in the developing countries, significantly lower than historical rates mainly due to the substitution to less carbon intensive fuels and improved efficiency. Global buildings CO₂ emissions under the business as usual scenario grow at a rate of 2.2% per year, increasing from 1664 Mt C in 1990 to 3171 Mt C in 2020. Of the near doubling in emissions from buildings projected to occur by 2020, 257 Mt C are from the industrialized countries, 636 Mt C are from the EE/FSU, and 614 Mt C are from developing countries.

The state of the art scenario⁴ assumes increased penetration of cost-effective energy efficiency technology, with gradual replacement of existing stock by currently available technologies by 2020. This translates to annual CO₂ emissions growth rates of 0.6% for industrialized countries, 2.6% for EE/FSU, and 1.8% for developing countries. Emissions from the total buildings sector increase from 1664 Mt C in 1990 to 2498 Mt C in 2020, at a rate of 1.4% per year. Overall, 46% of the growth in emissions occurs in the EE/FSU, 32% in developing countries and 22% in the industrialized countries.

The ecologically driven/advanced technology scenario assumes a more rapid uptake of current state of the art technologies and adoption of some advanced technologies that are not yet commercially available. Such changes are the result of aggressive energy efficiency policies and research and development that leads to viable products that are 5% to 15% more efficient than those assumed in the other two scenarios coupled with small changes in lifestyles that reduce energy use by 5 to 10%. Resulting annual growth rates are 0.2% for industrialized countries, 1.6% for EE/FSU, and 1.3% for developing countries. Under this scenario, global CO₂ emissions from buildings grow at a rate of 0.8% per year, to 2123 Mt C in 2020, 22% higher than 1990 levels.

Energy efficiency policy instruments

Both the state of the art and the ecologically driven/advanced technology scenarios rely upon increased use of en-

ergy-efficient technologies and practices to keep buildings CO₂ emissions below the near doubling expected under the business as usual scenario. To realize the energy savings inherent in such scenarios, there are at least four essential requirements: (1) real increases in energy prices; (2) effective use of energy efficiency policies; (3) major programs to transfer knowledge, technology, and tools for transforming markets to the EE/FSU and developing countries; and (4) continued efforts to pursue research and development in technologies and practices to increase energy efficiency in buildings.

Real increases in energy prices

Typically worldwide consumer energy prices do not reflect the full costs of energy production, transmission and distribution (as well as environmental costs) because these prices are often subsidized. In 1991 world fossil fuel subsidies reduced consumer energy prices by 20 to 25%. Subsidies are greatest in the developing countries and in EE/FSU, with the bulk of global fossil fuel subsidies in the latter region (Kozloff and Shobowale, 1994). Between 1979 and 1991, electricity prices in developing countries were on average 40% lower than electricity prices in industrialized countries. The disparity grew over the period from an average difference of US¢2.3/kWh (1986 US\$) between 1979 and 1984 to an average difference of US¢3.4/kWh between 1985 and 1991. A survey of electricity prices of over 60 developing countries found that electricity subsidies grew during the 1980s (World Bank, 1990). In 1991 the average electricity price in developing countries was US¢4/kWh while the marginal costs were about US¢10/kWh (Heidarian and Wu, 1994). Comparison of retail electricity prices to the marginal costs of supply found ratios of 50 to 60% in China, 66% in Brazil, 29% in Poland and 63% in Mexico in the late 1980s (Bates, 1993).

Energy prices in some areas are beginning to more closely reflect costs in response to commercialization of the electricity industry and investment by independent power producers (Anderson, 1995). For example, Thailand has essentially eliminated across the board subsidies, electricity prices in Korea have reached the level of costs, and energy prices in Poland are being adjusted to reflect full economic costs (World Bank, 1993; Larsen and Shah, 1992; Polish Ministry of Industry and Trade, 1992). In Chile energy prices rose following power sector privatization and reforms that eliminated government intervention in setting prices. In Colombia, Peru, Jamaica, Costa Rica and Bolivia privatization of part or all of the energy supply industry is currently taking place, and is expected to lead to deregulation of electricity prices in these countries (Bacon, 1995). After many years of trying, the Chinese government initiated significant energy price reforms⁵ starting in 1993. By 1994 90% of all coal was no longer subject to price regulations, and the price of this coal reflected most of the supply

⁴For the state of the art scenario, buildings and industrial energy use are both 37% of world primary energy use in 2020.

⁵For more information on subsidies and efforts at price reform, see Worrell *et al.*, 1996.

costs. In 1993 electricity price reforms in China led to prices for new power projects based on the cost of generation plus a return on capital. This change, plus higher prices for power from existing power plants, means that electricity prices may in time approach deregulated, marginal costs (Wang *et al*, 1995).

The international lending organizations, led by the World Bank, have been strong proponents of energy price deregulation in developing countries. The largest hurdle to such price increases involves the impact on low income consumers. This is a serious problem in many developing countries, since low-income urban families often spend a substantial portion of their income on energy. Recent surveys in urban areas of developing countries show the poorest 20% of the population spending 20% of their income on energy (Barnes *et al*, 1994). The impacts of higher energy prices on the urban poor can be mitigated in several ways. A low tariff for the lowest consumption block can be instituted, the so-called 'lifeline rate' in the USA. Subsidies for energy efficiency improvements can be targeted at low income urban dwellers. Such subsidies could moderate an increase in energy services. Because the lowest income population consumes a relatively small proportion of total energy in developing countries, revenue obtained from energy price increases would be expected to far exceed any subsidies to the low-income consumers.

Energy efficiency policies

Energy efficiency policies include use of financial incentives (direct subsidies, low interest loans and tax credits), building codes, appliance standards, information programs, utility integrated resource planning (including demand-side management) and market aggregation (or market pull) programs. Such policies accelerate adoption of energy-efficient technologies by addressing factors that often hinder implementation (Levine *et al*, 1996; Worrell *et al*, 1996).

Financial incentives to increase energy efficiency account for the majority of public sector spending on energy efficiency in most countries. For example, in the USA 84% (US\$230 million in 1991) of the Department of Energy's budget is spent on grants for retrofits to existing buildings (US Congress, OTA, 1992a). Most countries provide large incentives for electricity supply, leading to lower energy prices and disincentives to investment in energy efficiency. Recently electric utilities in some industrialized countries have provided targeted financial incentives for specific energy efficiency measures (eg energy-efficient lighting retrofits for commercial buildings). Other financial incentives have been provided from government and utility funds to provide a 'carrot' for the rapid commercialization of energy-efficient technology (eg more efficient refrigerators).

Building codes, which require minimum levels of energy efficiency in new construction, were adopted in at least thirty countries as of 1992 (Janda and Busch, 1993). Such codes range from voluntary goals to specific, comprehensive requirements directed toward savings in all areas of buildings energy use.

Appliance energy efficiency standards have been aggressively pursued in the USA. Since the passage of the National Appliance Energy Conservation Act (NAECA) in 1987, the federal government has mandated standards for such products as refrigerators, water heaters, furnaces and boilers, central air conditioners and heat pumps, room air conditioners, clothes washers, dryers, dishwashers, oven and lighting ballasts. The standards already in place are expected to reduce energy consumption in the USA by 1.1 EJ/year by the year 2000 and 2.75 EJ/year by 2015, avoiding the equivalent of thirty-one 500 megawatt power plants by the years 2000.

Information programs are designed to assist energy consumers in understanding and employing technologies and practices to use energy more efficiently. These programs aim to increase consumers' awareness, acceptance, and use of particular technologies or utility energy conservation programs. Examples of information programs include educational brochures, hot lines, videos, home energy rating systems, design-assistance programs, audits, energy use feedback programs, and labeling programs. Such programs tend to be most effective when coupled with other types of policies (eg financial incentives).

Utility integrated resource planning (IRP), which has been applied primarily in industrialized countries, is used to assess all options for meeting energy service needs, including utility sponsored end use efficiency or demand-side management (DSM) programs. DSM programs in the USA, which are now on the decline due to the current restructuring efforts, have promoted a wide variety of end use efficiency measures that are less costly than energy supply additions. Thailand launched a multi-sectoral DSM program to invest US\$189 million over five years (estimated to be half the cost of new supply) that is aimed at saving as much as 1400 MW of peak demand and 3400 GWh annually (Silver, 1996). Utilities in Mexico and Brazil have been active in DSM programs. Brazil's national electricity conservation program (PROCEL) is estimated to have saved the equivalent of a 250 MW power plant (Tavares, 1995).

An innovative policy mechanism to transform the market toward the production and consumption of more efficient products is 'market aggregation', or the organized use of buyer demand to stimulate new supplies of a product or service. NUTEK, the Swedish National Board for Industrial and Technical Development, has successfully undertaken several technology procurement projects for more efficient refrigerator-freezers, laundry equipment, high performance windows, computer monitors, office lighting, electronic ballasts and other products (Harris, 1995; Lewald and Bowie, 1993). In the USA recent activities include a federal procurement challenge, which directs all federal agencies to purchase energy efficient products that are in the top 25% of the market. In the USA a series of 'green' programs have been developed and implemented by the federal government to encourage consumers and/or manufacturers to purchase or produce more efficient technologies (US EPA, 1994).

Programs to transfer knowledge, technology and tools to the EE/FSU and developing countries

Efforts to promote energy efficiency have illuminated the need for closer collaboration between countries, especially in the areas of technological innovation, strengthening of local capacity and increased training and information. Technological solutions from industrialized countries may not be applicable to EE/FSU and developing countries without additional applied research and development. The technical operating environment in these countries is often different from that of industrialized countries. For example, poorer power quality, higher environmental dust loads and higher temperatures and humidity require different energy efficiency solutions than successful solutions in industrialized country conditions. Technologies that have matured and been perfected for the scale of production and market conditions in the industrialized countries are not necessarily the best choice for the smaller scale of production or different operating environments often encountered in other countries.

Another important arena for cooperation between countries involves the development and strengthening of local technical and policy making capacity in developing countries. There is inadequate attention to the development of institutional capacity and technical and managerial skills needed to make and implement energy efficiency policy. In some cases, new institutions (such as the energy efficiency centers that have been created in Russia, Eastern Europe and China) are needed to make certain that energy efficiency and alternative energy investments are treated equally with traditional supply investments and make it possible to 'bundle' a large number of demand-side investments into a large investment so that they can attract capital (Gadgil and Sastry, 1992).

Finally, there is a great need for increased training and information for EE/FSU and developing countries. Training efforts need to address all major elements of energy efficiency, including in-depth studies in engineering, economics, public policy, and management. Such training needs to be both theoretical and practical. Substantial assistance from industrialized countries in creating and conducting training courses may be necessary.

Research and development for energy efficient technologies and practices

Research and development (R&D) is the process that generates and refines new energy-efficient technologies. Different stages of R&D can be distinguished: basic research, applied research, experimental work and demonstration (OECD, 1993). In general, only large industries and governments have the resources and interest to conduct R&D. The buildings industry, in contrast, is highly fragmented. For example, single family residential construction firms in the USA alone number more than 90 000 (US Congress, OTA, 1992a). This fragmentation makes it difficult for the construction industry to pool its resources to conduct R&D. There is, however, R&D carried out by suppliers to the construction industry (eg insulation and window manufactur-

ers, heating, ventilation and cooling (HVAC) equipment and appliance manufacturers).

Government sponsored R&D has played a key role in developing and commercializing energy efficient technologies. Low e windows, electronic ballasts, and high efficient refrigerator compressors are examples of widely used technologies whose origins can be traced to public sector funding of research. Maintaining support for energy efficiency R&D is essential to ensure the availability of the next generation of energy efficient technologies.

Currently, widespread cutbacks in energy R&D, both public and private, threaten the continuity of the R&D effort. Between 1977 and 1992, public non-defense energy R&D funds decreased by 65% in the USA and by 33% in other OECD countries (Williams and Goldemberg, 1995). Private energy R&D has also declined, particularly as a result of utility and industry efforts to reduce costs to compete in more open markets. In 1990 less than 6% of the energy R&D budget of IEA countries was spent on energy efficiency and 6% was spent on renewable energy, while spending on nuclear fusion (46%), nuclear fission (11%) and fossil energy (18%) dominated (IEA, 1994b).

Conclusions

Recent studies found that without increased use of energy-efficient technologies and practices, global CO₂ emissions from buildings will nearly double by 2020. Even aggressive scenarios that include use of advanced technologies coupled with ecologically driven policies are not expected to keep buildings CO₂ emissions at 1990 levels due to the high demand growth expected in the developing countries and in the EE/FSU. However, the ecologically driven/advanced technology scenario shows reductions in emissions growth of 33% from a business as usual case. Realizing such savings will require aggressive use of energy efficiency policies, programs to transfer knowledge, technology, and tools for transforming markets to the EE/FSU and developing countries, and continued efforts to pursue research and development in technologies and practices to increase energy efficiency in buildings.

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